# Ocean U.S. GODAE: Global Ocean Prediction with the HYbrid Coordinate Ocean Model (HYCOM)

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## Introduction

During the past 5-10 years, a broad partnership of institutions has been collaborating in developing and demonstrating the performance and application of eddy-resolving, real-time global and basin-scale ocean prediction systems using the HYbrid Coordinate Ocean Model (HYCOM). These systems have been or are in the process of being transitioned for operational use by the U.S. Navy at the Naval Oceanographic Office (NAVOCEANO), Stennis Space Center, MS, and by the National Oceanic and Atmospheric Administration (NOAA) at the National Centers for Environmental Prediction (NCEP), Washington, D.C. The systems run efficiently on a variety of massively parallel computers and include sophisticated, but relatively inexpensive, data assimilation techniques for assimilation of satellite altimeter sea surface height and sea surface temperature as well as in-situ temperature, salinity, and float displacement. The partnership represents a broad spectrum of the oceanographic community, bringing together academia, federal agencies, and industry/commercial entities, spanning modeling, data assimilation, data management and serving, observational capabilities, and application of HYCOM prediction system outputs. All participating institutions were committed and the collaborative partnership provided an opportunity to leverage and accelerate the efforts of existing and planned projects, consequently producing a high quality product that should collectively better serve a wider range of users than would the individual projects.

The HYCOM partnership is a U.S. component of the international Global Ocean Data Assimilation Experiment (GODAE). GODAE is a coordinated international effort envisioning "a global system of observations, communications, modeling, and assimilation that will deliver regular, comprehensive information on the state of the oceans, in a way that will promote and engender wide utility and availability of this resource for maximum benefit to the community" (see Chassignet and Verron (2006) for a review). Navy applications, NOAA applications such as maritime safety, fisheries, the offshore industry, and management of shelf/coastal areas are among the expected beneficiaries of the HYCOM ocean prediction systems (http://www.hycom.org). More specifically, the precise knowledge and prediction of ocean mesoscale features is used by Navy, NOAA, the oil industry, and fisheries for an optimal use of their resources. Examples are optimal ship and submarine routing, search and rescue, oil spill drift application, monitoring of the open ocean ecosystems, fisheries management, short range coupled atmosphere-ocean forecasts, forecast of the coastal and near-shore environment, etc…

## Background

Numerical modeling studies over the past several decades have demonstrated progress in both model architecture and the availability of computational resources for the scientific community. Perhaps the most noticeable aspect of this progression has been the evolution from simulations on coarse-resolution horizontal/vertical grids outlining basins of simplified geometry and bathymetry and forced by idealized stresses, to fine-resolution simulations incorporating realistic coastal definition and bottom topography, forced by observational data on relatively short time scales. The choice of the vertical coordinate system in an ocean model however remains one of the most important aspects of its design. In practice, the representation and parameterization of the processes not resolved by the model grid are often directly linked to the vertical coordinate choice (Griffies et al., 2000). Oceanic general circulation models traditionally represent the vertical in a series of discrete intervals in either a depth, density, or terrain-following unit. Because none of the three main vertical coordinates (depth, density, and terrain-following) provide universal optimality, it is natural to envision a hybrid approach that combines the best features of each vertical coordinate. Isopycnic (density-tracking) layers work best for modeling the deep stratified ocean, levels at constant fixed depth or pressure are best to use to provide high vertical resolution near the surface within the mixed layer, and terrain-following levels are often the best choice for modeling shallow coastal regions. In HYCOM, the optimal vertical coordinate distribution of the three vertical coordinate types is chosen at every time step. The default configuration of HYCOM is isopycnic in the open stratified ocean, but makes a dynamically smooth transition to terrain-following coordinates in shallow coastal regions and to fixed pressure-level coordinates in the surface mixed layer and/or unstratified seas. In doing so, the model takes advantage of the different coordinate types in optimally simulating coastal and open-ocean circulation features (Chassignet et al., 2006, 2007). A user-chosen option allows specification of the vertical coordinate separation that controls the transition among the three coordinate systems. The assignment of additional coordinate surfaces to the oceanic mixed layer also allows the straightforward implementation of multiple vertical mixing turbulence closure schemes (Halliwell, 2004). The choice of the vertical mixing parameterization is also of importance in areas of strong entrainment, such as overflows.

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Data assimilation is essential for ocean prediction because (a) many ocean phenomena are due to nonlinear processes (i.e., flow instabilities) and thus are not a deterministic response to atmospheric forcing, (b) errors exist in the atmospheric forcing, and (c) ocean models are imperfect, including limitations in numerical algorithms and in resolution. Most of the information about the ocean surface's space-time variability is obtained remotely from instruments aboard satellites [Sea Surface Height (SSH) and Sea Surface Temperature (SST)], but these observations are insufficient for specifying the subsurface variability. Vertical profiles from expendable bathythermographs (XBT), conductivity-temperature-depth (CTD) profilers, and profiling floats (e.g., Argo, which measures temperature and salinity in the upper 2000 m of the ocean) provide another substantial source of data. Even together, these data sets are insufficient to determine the state of the ocean completely, so it is necessary to exploit prior knowledge in the form of statistics determined from past observations as well as our present understanding of ocean dynamics. By combining all of these observations through data assimilation into an ocean model, it is possible to produce a dynamically consistent depiction of the ocean. However, in order to have any predictive capabilities, it is extremely important that the freely evolving ocean model (i.e., non-data-assimilative model) has skill in representing ocean features of interest.

To properly assimilate the SSH anomalies determined from satellite altimeter data, the oceanic mean SSH over the altimeter observation period must be provided. In this mean, it is essential that the mean current systems and associated SSH fronts be accurately represented (position, amplitude, and sharpness). Unfortunately, the earth's geoid is not presently known with sufficient accuracy for this purpose, and coarse hydrographic climatologies (~0.5º-1º horizontal resolution) cannot provide the spatial resolution necessary when assimilating SSH in an eddy-resolving model (horizontal grid spacing of 1/10º or finer). At these scales of interest, it is essential to have the observed means of boundary currents and associated fronts sharply defined (Hurlburt et al., 2008). Figure 1 shows the climatological mean derived on a 0.5º grid using surface drifters by Maximenko and Niiler (2005) as well as the mean currently used in the Navy global HYCOM prediction system (see following section for details). The HYCOM mean was constructed as follows: a 5-year mean sea surface height field from a non-data assimilative 1/12º global HYCOM run was compared to available climatologies and a rubber-sheeting technique (Carnes et al., 1996) was used to modify the model mean in two regions, the Gulf Stream and the Kuroshio, where the western boundary extensions were not well represented and where an accurate frontal location is crucial for ocean prediction. Rubber-sheeting consists of a suite of computer programs specifically designed to operate on SSH fields, overlay contours from a reference field, and move masses of water in an elastic way (hence rubber-sheeting).
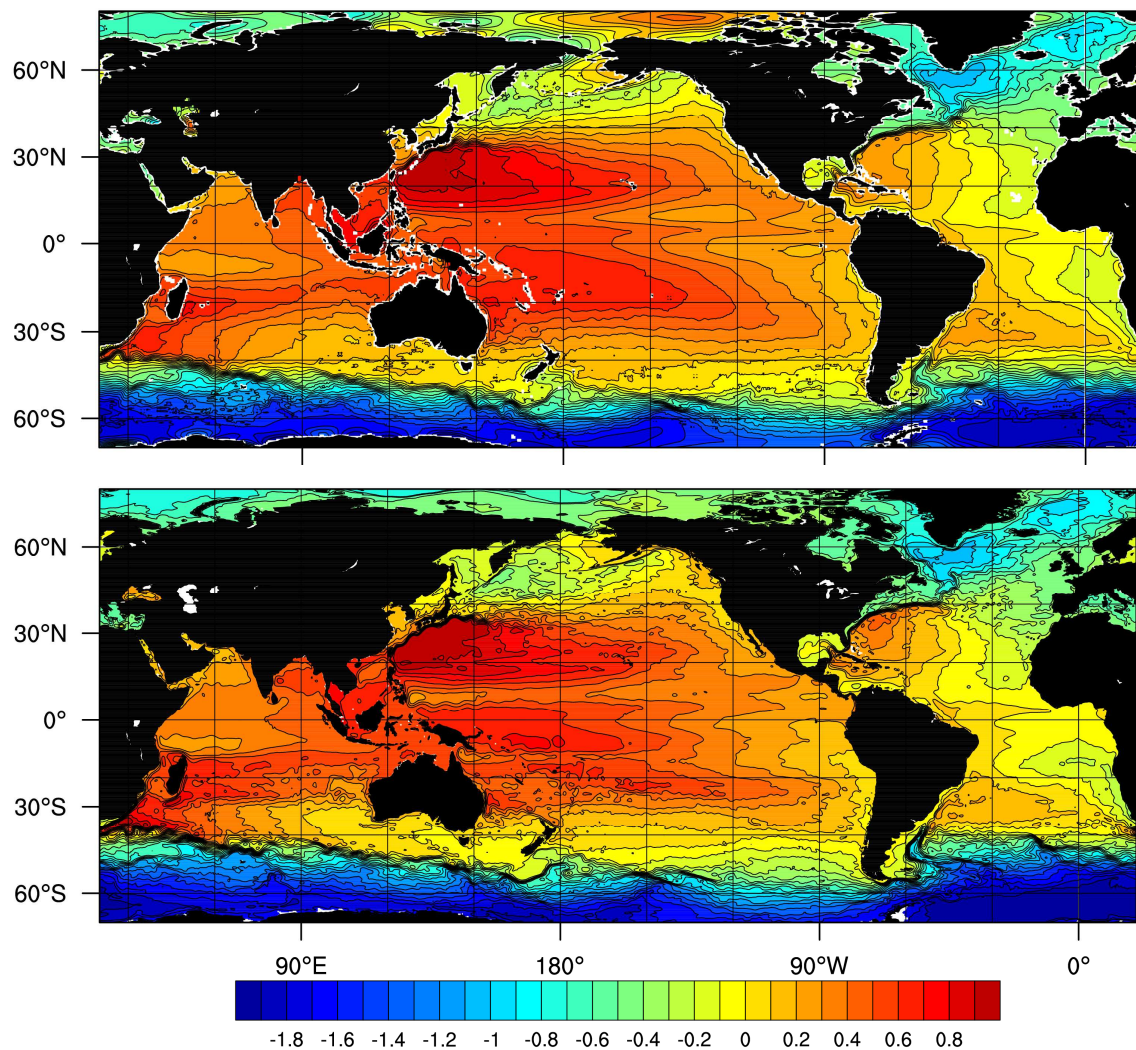
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**Figure 1**

Mean SSH (in cm) derived from surface drifters (Maximenko and Niiler, 2005) (top panel) and from a non-data assimilative HYCOM run corrected in the Gulf Stream and Kuroshio regions using a rubber-sheeting technique (bottom panel). The RMS difference between the two fields is 9.2 cm

## The HYCOM Ocean Prediction Systems (http://www.hycom.org)

Two systems are in the process of being evaluated for operational use by the U.S. Navy at the Naval Oceanographic Office (NAVOCEANO), Stennis Space Center, MS, and by the National Oceanic and Atmospheric Administration (NOAA) at the National Centers for Environmental Prediction (NCEP), Washington, D.C.

The first system is the NOAA Real Time Ocean Forecast System for the Atlantic (RTOFS). The Atlantic domain spans 25°S to 76°N with a horizontal resolution varying from 4 km near the U.S. coastline to 20 km near the African coast. The system is run daily with one-day nowcasts and five-day forecasts. Prior to June 2007, only the sea surface temperature was assimilated. In June 2007, NOAA implemented the 3D-Var data assimilation of i) sea surface temperature and sea surface height (JASON and GFO), ii) temperature and salinity profile assimilation (ARGO, CTD, moorings, etc.), and iii) GOES data. The model outputs are available at http://polar.ncep.noaa.gov/ofs/.

The second system is the pre-operational global U.S. Navy nowcast/forecast system using the 1/12° global HYCOM (6.5 km grid spacing on average, 3.5 km grid spacing at North Pole, and 32 vertical hybrid layers), which has been running in near real-time since December 2006 and in real-time since February 2007. The current ice model is thermodynamic (energy loan), but it will soon include more physics as it is upgraded to PIPS (based on the Los Alamos CICE ice model). The model is currently running daily on

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379 processors on the IBM Power 5+ at the Naval Oceanographic Office using a part of the operational allocation on the machine. The daily run (U.S. Navy requirement) consists of a 5 day hindcast and a 5 day forecast and takes about ~15 wall clock hours. The system assimilates sea surface height (Envisat, GFO, and Jason-1), ii) sea surface temperature (all available satellite and in-situ sources), iii) all available in-situ temperature and salinity profile (ARGO, CTD, moorings, etc.), and iv) SSM/I sea ice concentration. The three-dimensional multivariate optimum interpolation Navy Coupled Ocean Data Assimilation (NCODA) (Cummings, 2005) system is the assimilation technique. The NCODA horizontal correlations are multivariate in geopotential and velocity, thereby permitting adjustments (increments) to the mass fields to be correlated with adjustments to the flow fields. The velocity adjustments are in geostrophic balance with the geopotential increments, and the geopotential increments are in hydrostatic agreement with the temperature and salinity increments. Either the Cooper and Haines (1996) technique or synthetic temperature and salinity profiles (Fox et al., 2002) can be used for downward projection of SSH and SST. An example of forecast performance is shown in Figure 2.
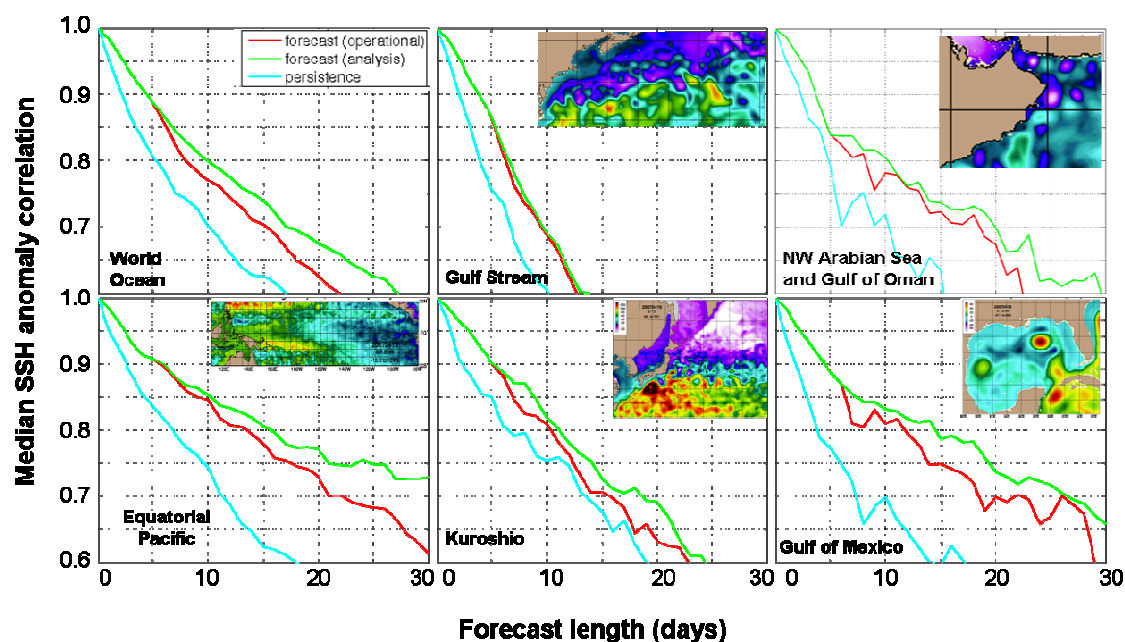


**Figure 2**

Verification of 30-day ocean forecasts: median SSH anomaly correlation vs. forecast length in comparison with the verifying analysis for the global HYCOM over the world ocean and five subregions. The red curves verify forecasts using operational atmospheric forcing, which reverts toward climatology after five days. The green curves verify "forecasts" with analysis quality forcing for the duration and the blue curves verify forecasts of persistence (i.e. no change from the initial state). The plots show median statistics over twenty 30-day HYCOM forecasts initialized during January 2004 - December 2005, a period when data from three nadir-beam altimeters, Envisat, GFO and Jason-1, were assimilated

The model outputs from the hindcast experiment are available through the HYCOM consortium web page, http://www.hycom.org. A validation of the results is underway using independent data with a focus on the large scale circulation features, sea surface height variability, eddy kinetic energy, mixed layer depth, vertical profiles of temperature and salinity, sea surface temperature and coastal sea levels. Figure 3 and 4 show some examples for the Gulf Stream region while Figure 5 documents the performance of HYCOM in representing the mixed layer depth. HYCOM is also an active participant in the international GODAE comparison of global ocean forecasting systems.
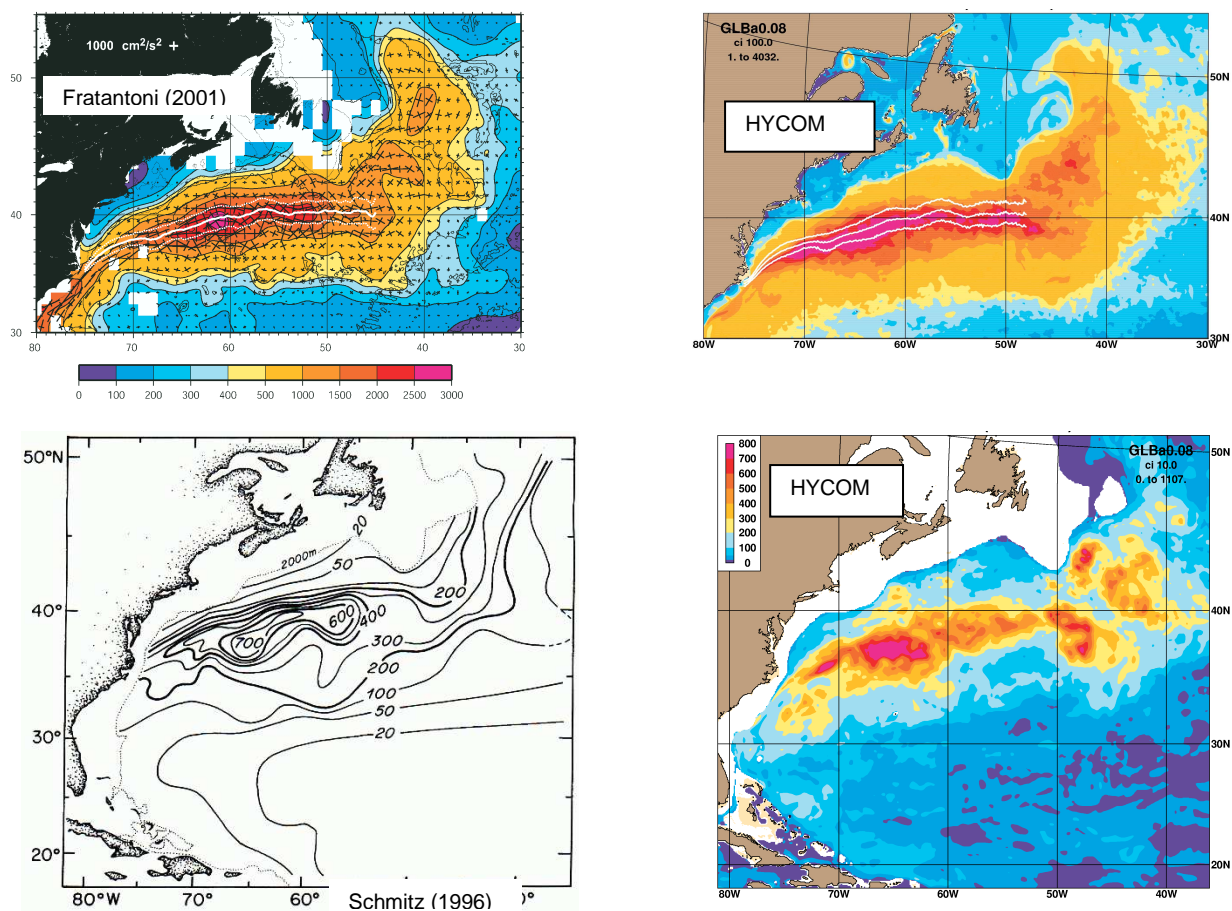
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***Figure 3***

Surface (top panels) and 700 m (lower panels) eddy kinetic energy from observations (left panels) and HYCOM over the period 2004-2006 (right panels). The observed surface eddy kinetic energy (upper left panel) is from Fratantoni (2001) and the 700 m eddy kinetic energy (lower left panel) is from Schmitz (1996). The units are in $cm^2/s^2$
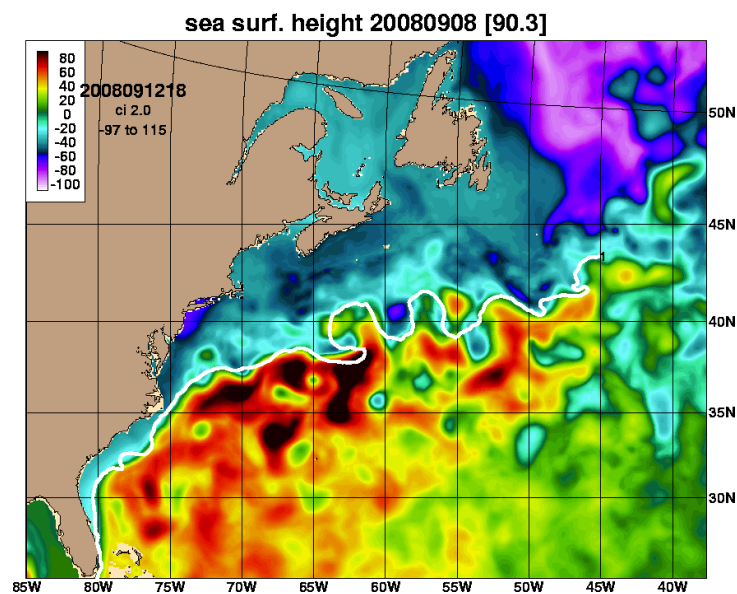


***Figure 4***

Modeled analysis of the sea surface height field on September 8, 2008. The white line represents the independent frontal analysis of sea surface temperature observations performed by the Naval Oceanographic Office

**Figure 5**

Median bias error (in meters) of mixed layer depth (MLD) calculated from simulated and approximately 66000 unassimilated observed profiles over the period June 2007-May 2008. Blue (red) indicates a simulated MLD shallower (deeper) than observed; 53% of the simulated MLDs are within 10 m of the observation and these are represented as gray. The basin-wide median bias error is -6.6 meters and the RMS error is 40 meters

The HYCOM data distribution team developed and implemented a comprehensive data management and distribution strategy that allowed easy and efficient access to the global HYCOM-based ocean prediction system outputs to (a) coastal and regional modeling groups, (b) to the wider oceanographic and scientific community including climate and ecosystem researchers, and (c) the general public. The basic idea consists of the setup of a web server that acts as a gateway to backend data management, distribution and visualization applications (http://www.hycom.org/dataserver). These applications enable end users to obtain a broad range of services such as browsing of datasets, gif images, NetCDF files, FTP request of data etc. The 100 Terabytes HYCOM Data Sharing System is built upon two existing software components: the Open Project for a Network Data Access Protocol (OPeNDAP) and the Live Access Server (LAS). These tools and their use to distribute the data are described below. In the current setup, the OPeNDAP component provides the middleware necessary to access distributed data, while the LAS functions as a user interface and a product server. The abstraction offered by the OPeNDAP server also makes it possible to define a virtual data set that LAS will act upon, rather than physical files. An OPeNDAP "aggregation server" utilizes this approach to append model time steps from many separate files into virtual datasets. The HYCOM Data service has been in operation for the last four years and has seen a steady increase in the user base. In the last year, the service received approximately 20,000 hits per month. In addition to the numerous requests from educational institutes and researchers this service has been providing near real-time data products to several private companies in France, Portugal, and the USA.

An important attribute of the data assimilative HYCOM system is its capability to provide boundary conditions to even higher horizontal and vertical resolution regional and coastal models. The current horizontal and vertical resolution for the global forecasting system marginally resolves the coastal ocean [7 km at mid-latitudes, with up to 15 terrain-following (σ) coordinates over the shelf], but is an excellent starting point for even higher resolution coastal ocean prediction systems. Several partners within the HYCOM consortium evaluated the boundary conditions and demonstrated the value added of the global and basin HYCOM data assimilative system outputs for coastal ocean prediction models. The inner nested models may or may not be HYCOM, i.e. the nesting procedure can handle any vertical grid choice. Outer model fields are interpolated to the horizontal and vertical grid of the nested model throughout the entire time interval of the nested model simulation at a time interval specified by the user, typically once per day. The nested model is initialized from the first archive file and the entire set of archives provides boundary conditions during the nested run, insuring consistency between initial and boundary conditions. This procedure has proven to be very robust. Figure 6 shows an example of the ROMS West Florida Shelf domain embedded in the U.S. Navy HYCOM ocean prediction system (Barth et al., 2008).
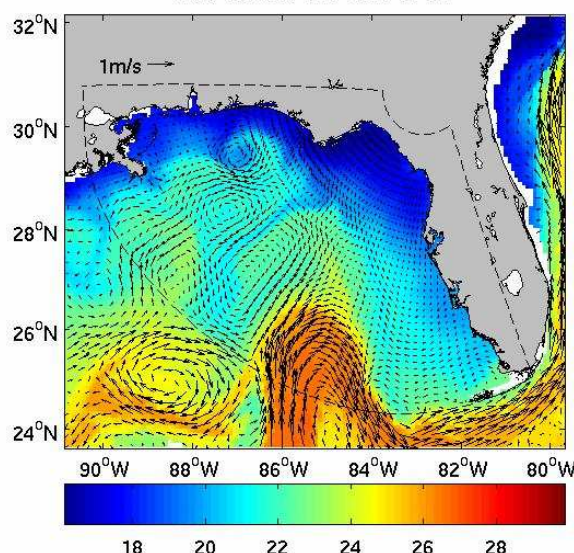
*Figure 6*

Sea surface temperature (in degree Celsius) and surface velocity fields from the ROMS West Florida Shelf domain (inside the dashed lines) and the HYCOM ocean prediction system (outside the dashed lines)

## Outlook

The long term goals of the HYCOM consortium for the global domain are to a) add 3-D and 4-D VAR data assimilation, b) increase the horizontal resolution of the global domain to 1/25°, c) implement zero depths coastlines with wett ing and drying, and c) include tides. The scientific goals will include, but will not be limited to a) evaluation of the internal tides representation in support of field programs, b) evaluation of the global model's ability to provide boundary conditions to very high resolution coastal models, c) interaction of the open ocean with ice, d) shelf-deep ocean interactions, e) upper ocean physics including mixed layer/sonic depth representation, and f) mixing processes. Other research activities will focus on coupled ocean-atmosphere prediction; bio–geo–chemical–optical and tracer/contaminant prediction; ecosystem analysis and prediction; and earth system prediction (i.e. coupled atmosphere-ocean-ice-land).

## Acknowledgements

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